

Ministry of Transportation
Materials Engineering and Research Office Report



**Preventative Measures for
Alkali-Silica Reaction: The
Kingston Outdoor Exposure Site
for ASR - After 16 Years**

MERO-031

Publication Title	Preventative Measures for Alkali-Silica Reaction: The Kingston Outdoor Exposure Site for ASR - After 16 Years
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Abstract	<p>The selection of measures to prevent alkali-silica reaction in concrete requires confidence that the selected measure will work over the life of the structure. It is crucial that the results of short-term laboratory tests be correlated to long-term performance of concrete in structures. Without this relationship being demonstrated, engineers cannot have confidence that the selected preventive measure will be effective in the long term. In an effort to provide correlation between short-term laboratory tests and long-term performance, an outdoor exposure site was established in Kingston, Ontario in 1991. The alkali-silica reactive aggregate was the Spratt siliceous limestone aggregate, which was combined into six concrete mixtures using various cements and supplementary cementing materials. Both blocks 0.6 x 0.6 x 2 m, and 0.2 x 1.2 x 4 m pavement slabs on grade were cast. The concrete made with high-alkali cement cracked at an age of 5 years. Where the high-alkali cement was replaced with various amounts of supplementary cementing materials, expansion has been considerably less and only very minor cracking has occurred. The following materials have been shown to be more or less effective at reducing damage: 25% ground granulated blast-furnace slag, 18% Type F fly ash, low-alkali cement (< 0.6% Na₂O_e). The most effective measures for control of ASR cracking and expansion were 50% ground granulated blast-furnace slag and a ternary blend of 25% slag plus 3.8% silica fume interground with a high-alkali Portland cement. Of those two concretes, the one that also exhibited superior de-icer salt scaling resistance was the ternary mixture.</p>
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In addition, cores were extracted after 12 years and examined petrographically using the damage rating index, by thin section microscopy, and by electron microscopy, SEM/EDX. Other properties measured were chloride penetration profiles on the sidewalk sections, chloride diffusion values, and rapid chloride permeability.

Key Words	Concrete, alkali-silica reaction, fly ash, outdoor exposure, preventive measures, slag, silica fume, supplementary cementing materials.
Distribution	Unrestricted technical audience.



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Executive Summary

The selection of measures to prevent alkali-silica reaction in concrete requires confidence that the selected measure will work over the life of the structure. It is crucial that the results of short-term laboratory tests be correlated to long-term performance of concrete in structures. Without this relationship being demonstrated, engineers cannot have confidence that the selected preventive measure will be effective in the long term. In an effort to provide correlation between short-term laboratory tests and long-term performance, an outdoor exposure site was established in Kingston, Ontario in 1991. The alkali-silica reactive aggregate was the Spratt siliceous limestone aggregate, which was combined into six concrete mixtures using various cements and supplementary cementing materials. Both blocks 0.6 x 0.6 x 2 m, and 0.2 x 1.2 x 4 m pavement slabs on grade were cast. The concrete made with high-alkali cement cracked at an age of 5 years. Where the high-alkali cement was replaced with various amounts of supplementary cementing materials, expansion has been considerably less and only very minor cracking has occurred. The following materials have been shown to be more or less effective at reducing damage: 25% ground granulated blast-furnace slag, 18% Type F fly ash, low-alkali cement ($< 0.6\% \text{ Na}_2\text{Oe}$). The most effective measures for control of ASR cracking and expansion were 50% ground granulated blast-furnace slag and a ternary blend of 25% slag plus 3.8% silica fume interground with a high-alkali Portland cement. Of those two concretes, the one that also exhibited superior de-icer salt-scaling resistance was the ternary mixture.

In addition, cores were extracted after 12 years and examined petrographically using the damage rating index, by thin section microscopy, and by electron microscopy, SEM/EDX. Other properties measured were chloride penetration profiles on the sidewalk sections, chloride diffusion values, and rapid chloride permeability.

Keywords: Alkali-silica reaction, fly ash, outdoor exposure, preventive measures, slag, silica fume, supplementary cementing materials.

Preventative Measures for Alkali-Silica Reaction: The Kingston Outdoor Exposure Site for ASR - After 16 Years

INTRODUCTION

The Province of Ontario contains many sources of alkali-reactive concrete aggregates, which have been studied since the 1950's. Two types of reaction are found: (a) alkali-silica reaction (ASR) with cryptocrystalline quartz found in chert, argillites, greywackes, sandstones, granites, and slightly siliceous limestone, and (b) the alkali-carbonate rock reaction (ACR) found with dolomitic limestone (Rogers et al, 2000). Of the six major sources of Portland cement manufactured in the province, five were, until relatively recently, high alkali ($> 0.8\%$ Na_2Oe), and one was of low-alkali content ($< 0.6\%$ Na_2Oe). In the case of the ACR, low-alkali cement does not eliminate cracking unless alkalies are extremely low (< 0.40 or 0.45% Na_2Oe) (Swenson and Gillott, 1960). Because of the restricted availability of low-alkali cement, and because of its lack of efficacy with the alkali-carbonate reaction, it has rarely been specified. As a result, the traditional means of preventing alkali-aggregate reactions in Ontario has been to specify the use of non-reactive aggregates. Non-reactivity has normally been determined by both field performance and laboratory testing. There are, however, excellent sources of granulated blast-furnace slag available and, more recently, fly ashes and silica fume-blended cements have become available. There is a desire to be able to use these supplementary cementing materials to prevent deleterious expansion as an alternative to the use of non-reactive aggregates or low-alkali cement. In the mid-1980's, experiments were begun to see if ground granulated blast-furnace slag (ggbfs) was effective at reducing expansion of alkali-carbonate reactive (ACR) dolomitic-limestone aggregate. These studies involved laboratory testing and construction of an outdoor exposure site. The results were disappointing because the slag was found to have no long-term beneficial effect and, on the contrary, seemed to promote ACR expansion in the long term (Rogers and Hooton, 1992). An important lesson from this study was that testing in the laboratory up to one year could give misleading information about the long-term prognosis.

The selection of measures to prevent alkali-silica reaction in concrete requires confidence that the selected measure will be effective for the life of the structure. Structures are typically designed to last for at least 75 years and often for longer. Numerous laboratory studies have shown that supplementary cementing materials (SCM's) are effective at preventing deleterious expansion in mortar and small concrete (CSA A23.2-14A, ASTM C1293) specimens up to an age of one or two years (Duchesne and Bérubé, 1994; Thomas and Innis, 1999). One of the problems in laboratory studies is leaching of the highly soluble alkalies from the small laboratory test specimens. This removal of alkalies from the concrete slows and eventually stops reaction and expansion (Rogers and Hooton, 1991). In real concrete elements and structures, because of the longer transport distances, this leaching of alkalies, which usually occurs near the surface, rarely or never takes place to an extent that would stop long-term reaction and expansion. It is crucial that the results of laboratory tests be

correlated to long-term performance of concrete in structures. Without this relationship being demonstrated, engineers cannot have confidence that the selected measure will be effective in the long term. There have been few field performance studies to confirm that the beneficial effects observed in the laboratory carry into the future.

EXPERIMENTAL DESIGN

The main purpose of the outdoor exposure demonstration was to show the long-term effectiveness of a variety of SCM's at preventing deleterious expansion with a highly alkali-silica reactive aggregate from Ontario and also to provide a correlation between short-term laboratory tests and long-term performance.

A variety of SCM combinations were chosen. The types and proportions used are shown in Table 1. The available supply of blended silica fume cement (CSA Type 10 SF) on the day of batching resulted in the low 3.8% replacement level used in Mixture 4. The number of mixtures was limited to a total of six for practical reasons. Reinforced and non-reinforced beams and pavement slabs were chosen as the elements for demonstration because they simulate the types of structures typically used in highway infrastructure. Details of the compositions of the cementing materials can be found in a paper by Afrani and Rogers, 1994.

Table 1. Concrete Mixture Designs, Binder Alkalies, and Hardened Concrete Properties

	Description	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
Portland cement	high-alkali, kg/m ³ , 0.79% Na ₂ O _e	207.5 (50%)	350.6 (82%)	311.3 (75%)	100.4 (24%)	...	415 (100%)
	low-alkali, kg/m ³ , 0.46% Na ₂ O _e	...	...	...	...	415 (100%)	...
Silica fume	silica-fume cement, kg/m ³ , 0.88% Na ₂ O _e , Note 1	...	...	...	210.8 (51%)	...	...
Slag	granulated blast-furnace slag, kg/m ³ , 0.66% Na ₂ O _e	207.5 (50%)	...	103.8 (25%)	103.8 (25%)	...	...
Fly ash	Type F, kg/m ³ , 0.27% Na ₂ O _e	...	77.0 (18%)	...	...	...	...
Total binder	kg/m ³	415	427.6	415.1	415	415	415
Fine aggregate	natural sand, kg/m ³ + 3% moisture	622	606	628	622	636	636
Coarse aggregate	Spratt quarry, kg/m ³ + 1% moisture	1152	1152	1152	1152	1152	1152
Strengths	Effective w/cm	0.38	0.37	0.39	0.34	0.40	0.39
27 day	compressive strength, MPa	40.0	39.0	41.8	47.9	39.6	35.6
	splitting tensile, MPa	3.7	3.4	3.8	4.0	3.8	3.5
82 day	compressive strength, MPa	44.9	50.0	42.7	52.8	46.2	44.3
	splitting tensile, MPa	3.9	3.8	4.3	4.1	4.3	3.8
1 year	compressive strength, MPa	49.7	52.4	50.9	63.2	54.2	49.2
	splitting tensile, MPa	3.8	4.3	3.3	4.8	3.4	3.2
7.25 year	compressive strength, MPa	58.5	60.4	59.0	61.8	62.2	57.9
	splitting tensile, MPa	3.6	3.8	3.7	3.6	4.4	3.5
Alkali content	kg/m ³ Na ₂ O equiv. of mix, Note 2	3.01	2.98	3.14	3.33	1.91	3.28

Note 1: Portland silica fume cement (CSA Type 10 SF) contained 7.5% silica fume for an effective silica fume content of 3.8%.

Note 2: No alkali such as NaOH or KOH was added to any mixture; the alkali values given are of those of the cement and SCM.

AGGREGATES

The alkali-silica reactive aggregate chosen for the demonstration was the Spratt aggregate from a quarry near Ottawa, Ontario. The aggregate had been crushed in 1985 and placed in a 120-tonne stockpile. The aggregate is a Middle Ordovician, medium-grey, fine crystalline limestone. The material is slightly siliceous (9% SiO₂) and has been used as a convenient alkali-silica reactive aggregate for investigating alkali-silica reaction expansion tests (Rogers and Hooton, 1991; Fournier and Malhotra, 1996; Bleszynski et al, 2000). The stone met all of the normal physical requirements for concrete aggregate and was well graded from 20 to 5 mm. The fine aggregate for the outdoor exposure site was a local source of non-reactive natural sand composed of igneous and high-grade metamorphic rocks and derived minerals. The sand had a long history of satisfactory performance in concrete made with high-alkali cement.

CONSTRUCTION

Mixing and placement of the concrete mixtures was described in a paper by Afrani and Rogers, 1994. The coarse aggregate was proportioned and mixed with various cements and SCM's in 3m³ batches using a Ready Mix Batching Plant and a Transit Mixer. The plant was about 5 minutes travel from the test site.

All six mixtures were batched on one day because, in order to supply the quantities required, a concrete batching plant was needed. The normal non-reactive coarse aggregate had to be removed from the storage bins and replaced with the reactive Spratt aggregate. This meant that no other concrete could be batched for customers on that day. The two cement silos at the plant were filled with high-alkali Portland cement and ground granulated blast-furnace slag. The other materials were added by hand from 20 L plastic buckets or from bags. The concrete mixtures were required to be air-entrained, which is almost universally required for Canadian outdoor conditions. The air content in the freshly mixed concrete varied from 5.7 to 6.4% at the batching plant and from 4.0 to 5.1% at the time of placement. The slumps of the concretes ranged from 60 to 85 mm.

A non-reinforced beam 0.6 x 0.6 x 4 m and a steel reinforced beam (steel area of 1.41%) of the same size and a 0.2 x 1.2 x 4 m pavement slab were cast from each mixture. The concrete was compacted and finished by professional concrete finishers. The pavement slabs and beams were cured with wet burlap and plastic sheets for 4 days after placement.

MEASUREMENT OF EXPANSION AND TEST SAMPLES

Before the concrete had set, stainless steel bolts 100 mm long were placed vertically in the upper surface flush with the surface of the concrete of both the slabs and beams. These bolts had holes drilled in the end to accept the measuring pins of a dial gauge measuring device with a nominal length of 508 mm readable to 0.0001 inch (0.0025 mm). Six measuring stations were set on the surface of each beam and six measuring stations on each slab.

Three concrete prisms were cast (75 x 75 x 400 mm) from each mixture, demoulded after three days, and initial length measured. These beams were then individually wrapped in paper towels and placed in a sealed plastic bag with approximately 100 ml of water and

placed on a rack in a sealed box with water in the bottom. The boxes were then stored at 38°C. Accelerated mortar bar testing (CSA A23.2-25A) was conducted using the Spratt coarse aggregate, crushed to sand size. All of the cements and SCM's used were tested in those proportions used in the field concrete. The water to cementitious materials ratio was set at 0.50 for all mortar mixtures. In some cases, the mixtures were re-tested as a check of the reproducibility of the test procedure.

MONITORING AND MEASUREMENT

In the week following casting, and after the concrete had cooled to ambient temperature, the initial measurements of the length of the pavement slabs and beams were made. This was done three times on different days to ensure that errors had not occurred. Thereafter, measurements were made close to the anniversary of construction, as far as possible at the same temperature conditions as had been present at the time of initial measurement (14-15°C). The concrete prisms stored at 38°C were measured following the requirements of CSA A23.2-14A at various ages up to one year and yearly thereafter. Concrete cylinders stored at 23°C were tested for strength properties at various ages.

The temperature microclimate of the exposure site has been monitored using a data logger and thermocouples. Temperature has been measured within the concrete at depths of 50 mm, 150 mm, and 300 mm every hour for 8 years. The climate of the site is moderately severe, with many freeze-thaw cycles every winter and an annual average precipitation of about 800 mm. Depending on the temperatures chosen to best represent a freeze and a thaw, the annual average number of freeze-thaw cycles is shown in Table 2 (Nokken *et al.*, 2004). The minimum concrete temperatures recorded were -24°C and maximum temperatures were 42°C. Table 3 shows the average July and January temperatures of the concrete. These are, respectively, the hottest and coldest months. It can be seen that, in January, the concrete was frozen with an average temperature of between -3 and -7°C. The slabs were slightly warmer than the beams because of heat transfer from below and possibly the insulating properties of occasional snow cover. In July, the concrete was at an average temperature of between 25 and 29°C and was higher than air temperature because of solar effects.

Table 2. Average Number of Freezing Cycles for 5 Consecutive Winters (from 1992/93 to 1996/97) and average January and July temperatures at the Kingston site

	Average Number of Freezing Cycles					Average Temperatures	
	0°C	-2°C	-3°C	-5°C	-8°C	January	July
Assumed Freezing Temp.	0°C	0°C	0°C	0°C	0°C		
Assumed Thawing Temp.	0°C	0°C	0°C	0°C	0°C		
Air (150 mm above slab)	96	62	51	39	24	-6.2	23.9
Beam (50 mm depth)	65	46	42	30	21	-7.4	25.3
Beam (300 mm depth)	29	16	14	8	5	-6.1	24.8
Slab (50 mm depth)	47	26	25	12	6	-3.6	29.3
Slab (100 mm depth)	36	14	10	4	3	-3.0	28.7

After 12 years, a series of 100 mm diameter cores was taken from each slab and beam for each concrete mixture. These cores were tested: (a) petrographically in thin sections, by Scanning Electron Microscopy using Back-Scattered Imaging and Energy-Dispersive X-Ray Analysis, depth of carbonation, and measuring Damage Rating Index on polished sections, (b) for chloride bulk diffusion by ASTM C1556, permeability index using ASTM C1202, and (c) de-icer chloride penetration into the slabs. Expansion measurements in the field have continued and data up to 16 years have been collected.

Table 3. Summary of Accelerated Mortar Bar Expansion Data (CSA A23.2-25A)

Mix #	Binder Type and Proportions	Mortar Bar Expansion in Per Cent			
		14 Day	21 Day	28 Day	14 Day Duplicate
1	HAPC, 50% + GGBFS, 50%	0.059	-	-	-
2	HAPC, 82% + fly ash, 18%	0.111	0.171	0.249	0.118
3	HAPC, 75% + GGBFS, 25%	0.187	-	-	-
4	HAPC, 25% + silica fume cement, 75% + GGBFS, 25%	0.041	0.089	0.153	-
5	LAPC, 100%	0.435	0.484	0.553	0.471
6	HAPC, 100%	0.315	0.378	0.480	0.330
-	Silica fume cement, 100%	0.153	-	-	-
-	Silica fume cement, 75% + ggbfs, 25%	0.021	0.031	0.057	0.065
-	HAPC, 90% + fly ash, 10%	0.263	0.351	0.449	0.294
-	HAPC, 75% + fly ash, 25%	0.047	0.093	0.156	0.054
-	HAPC, 60% + fly ash, 40%	0.017	0.031	0.052	0.011
-	HAPC, 85% + GGBFS, 15%	0.232	-	-	-
-	HAPC, 65% + GGBFS, 35%	0.128	-	-	-
-	HAPC, 60% + GGBFS, 40%	0.110	-	-	-
-	HAPC, 40% + GGBFS, 60%	0.027	-	-	-

Note: HAPC = high-alkali Portland cement
LAPC = low-alkali Portland cement
GGBFS = ground granulated blast-furnace slag

RESULTS AND DISCUSSION

Concrete mixture design data is summarized in Table 1, together with the results of strength testing. Details of cement composition and further data on concrete properties and performance will be found in a paper by Afrani and Rogers (1994).

A paper providing the results after 8 years exposure was previously published (Rogers et al, 2000). Table 4 shows the results of accelerated mortar bar expansion testing. Figure 1 shows the 38°C expansion of the concrete prisms made with the six different mixtures. Figures 2, 3, and 4 show the length change of the unreinforced beams, reinforced beams, and pavement

slabs, respectively. In these data, no correction has been made for the thermal expansion effects caused by making annual measurements at slightly different ambient temperatures each year. As a result, the curves are not smooth. The error is judged to be small. In Figure 2, it can be seen that expansion of Mixture 6 (high-alkali cement) started after 2 years, and visible cracking was first observed at an age of 5 years. By 7 years, pattern cracking was obvious on all beam surfaces of Mixture 6.

Figure 5 shows that the presence of 1.41% by area of longitudinal steel reinforcement has restrained the expansion by 40% of that of the non-reinforced beams of Mixture 6 (high-alkali cement). Hobbs (1988) reported that 0.91% steel reinforcement gave a significantly greater reduction of expansion of between 65 and 70%. In his studies, the unrestrained expansion was significantly greater (0.5-0.8% at about 100 days) using an artificial reactive aggregate under laboratory conditions. This may have given unrealistic restraint compared with real conditions where greater creep may be expected.

Table 4. Chloride Bulk Diffusion and Rapid Chloride Results on 14-Year Cores from Beams

Concrete Mixture	Mix # and Position of Core	ASTM C1556 (42 days Ponding)		ASTM C1202
		Surface Chloride, Cs (mass %)	Bulk Diffusion, Da (m ² /s)	(Coulombs)
Mix 1 50% GGBFS	1. Surface	0.3287	9.23E-12	274
	1. Centre	0.6058	0.99E-12	316
Mix 2 18% FA	2. Surface	0.2113	10.7E-12	442
	2. Centre	0.7492	2.58E-12	346
Mix 3 25% GGBFS	3. Surface	0.1718	8.16E-12	835
	3. Centre	0.6039	6.29E-12	836
Mix 4 25% GGBFS 3.8% SF	4. Surface	0.1300	4.88E-12	244
	4. Centre	0.4443	1.58E-12	232
Mix 5 100% LAPC	5. Surface	0.2666	8.97E-12	1057
	5. Centre	0.7790	13.2E-12	1014
Mix 6 100% HAPC	6. Surface	0.1787	4.70E-12	876
	6. Centre	0.7301	5.77E-12	1690
Mix 6 (Reinforced Beam)	6R. Surface	0.3869	4.87E-12	1450
	6R. Centre	0.7461	7.87E-12	1383

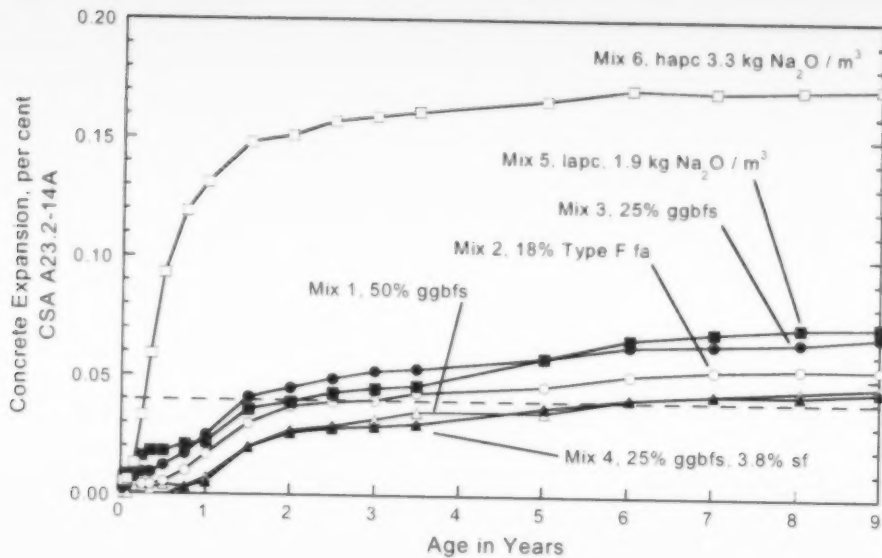


Figure 1. Expansion of Concrete Prisms in the Laboratory at 38°C

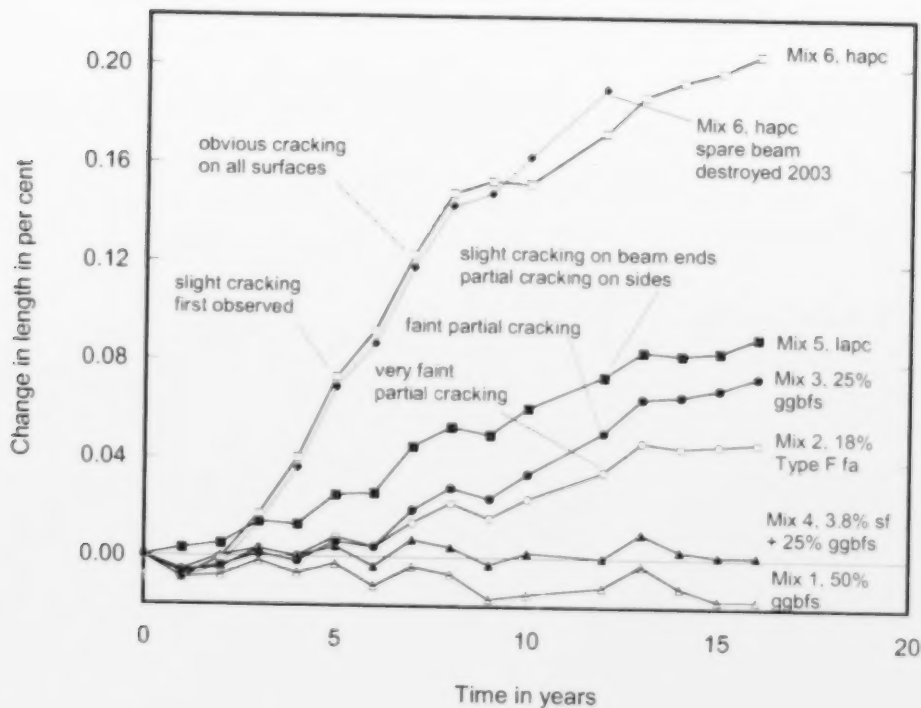


Figure 2. Expansion of Outdoor Exposed Unreinforced Concrete Beams

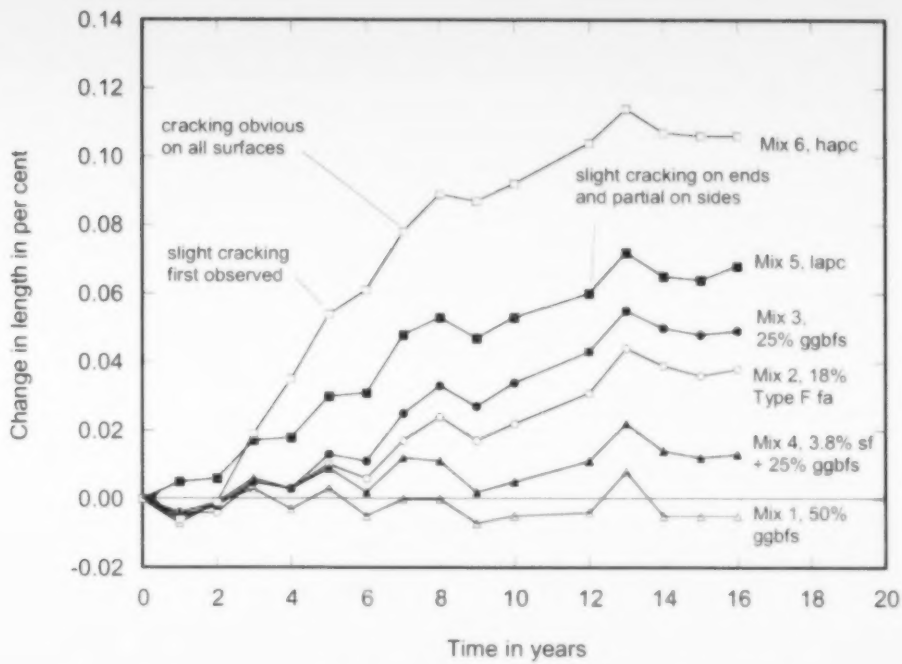


Figure 3. Expansion of Outdoor Exposed Reinforced Concrete Beams

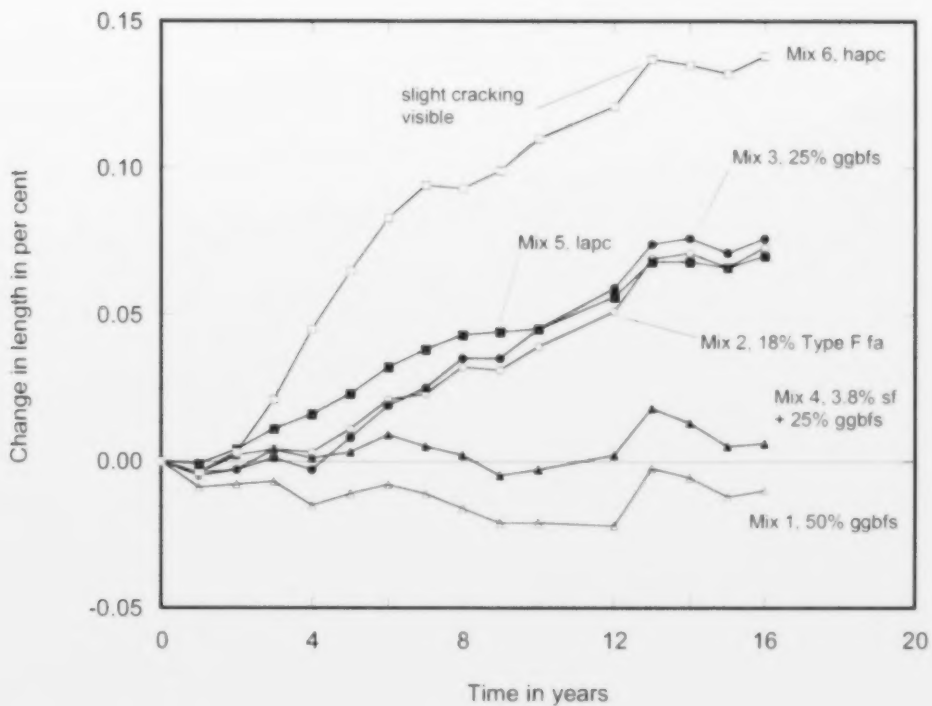


Figure 4. Expansion of Outdoor Exposed Pavement Slabs

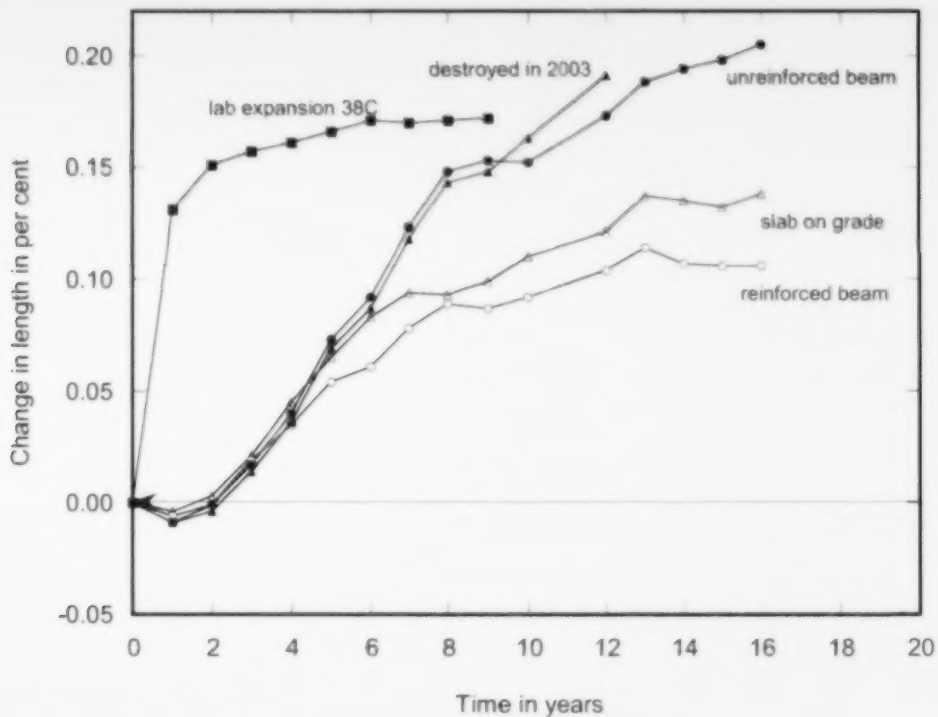


Figure 5. Expansion of Mixture 6 (High-Alkali Cement) in Various Elements

Sample ID	ASTM C1556 (42 Days Ponding)		ASTM C1202
	Cs (mass %)	Da (m2/s)	(coulombs)
Mix 1 -1 S	0.673	2.44 E-12	409
Mix 1 -2 S	0.622	2.24 E-12	245
Mix 2 -1 S	0.866	2.89 E-12	654
Mix 2 -2 S	0.687	7.50 E-12	541
Mix 3 -1 S	0.977	3.94 E-12	1097
Mix 3 -2 S	0.774	5.40 E-12	851
Mix 4 -1 S	0.728	1.74 E-12	212
Mix 4 -2 S	0.674	1.67 E-12	201
Mix 5 -1 S	0.734	14.9 E-12	1901
Mix 5 -2 S	0.651	18.3 E-12	2161
Mix 6 -1 S	0.819	8.67 E-12	1826
Mix 6 -2 S	0.737	8.75 E-12	1509

Table 5. Chloride Bulk Diffusion and Rapid Chloride Results on 14-Year Cores from Slabs

In contrast to the high-alkali cement beams, the companion pavement slab has shown little cracking beyond that noted on the edges at 5 years. Figure 6 shows that, up to about 6 years, the expansion of the slab was similar to that of the non-reinforced beams. After 6 years, the expansion has slowed so that, after 9 years, the expansion of the slab is about that of the reinforced beam. The reason for this is unknown. It is possible that expansion is being constrained by a combination of friction between the slab and the underlying and surrounding well-compacted granular base and restraint of the 60 mm thick asphaltic concrete that was installed around the perimeter of the slab. Both these materials have a low modulus compared with that of the concrete and it is hard to conceive that they would be able to slow expansion.

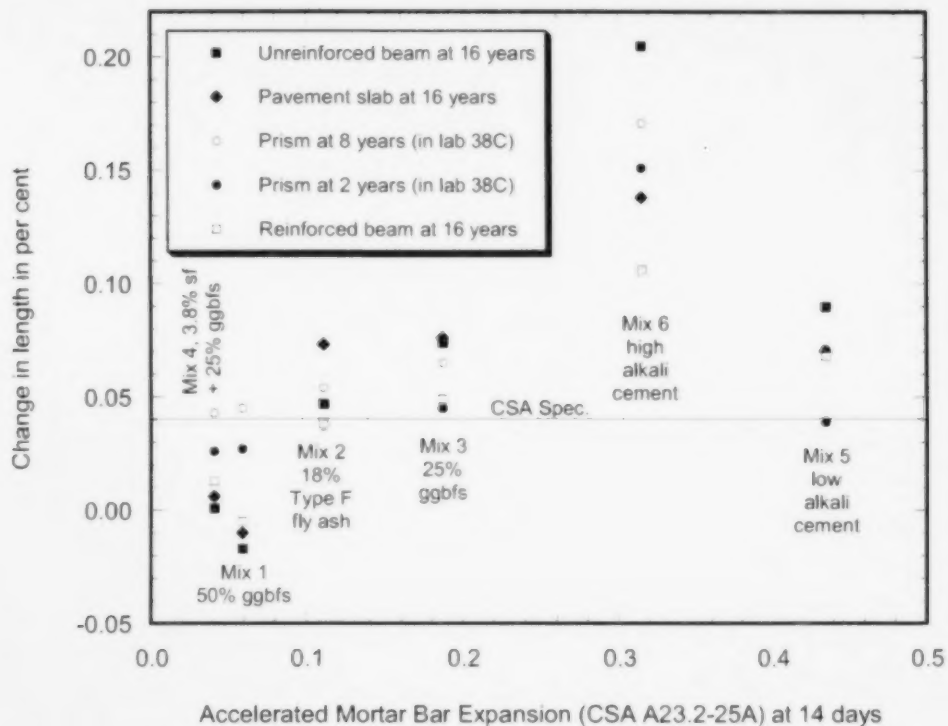


Figure 6. Mortar Bar Expansion Versus Concrete Field Expansion at 16 Years

PETROGRAPHIC AND SEM EXAMINATION

Previous petrographic examination of concrete cylinders stored moist in sealed plastic bags at 23°C for 7 years in the laboratory showed obvious signs of alkali-silica reaction in Mixture 6 (high-alkali cement). Micro fractures were frequently found in both the paste and coarse aggregates and these cracks were usually filled with alkali-silica reaction products. Air voids adjacent to coarse aggregate particles and cracks in the mortar were usually filled or lined with gel. Cracks in coarse aggregate were filled with a very fine crystalline mineral. Concrete representing the other mixtures showed no significant signs of alkali-silica related cracking or products. It should be noted that the presence or absence of alkali-silica gel in laboratory samples may not be representative of the concrete in outdoor exposure.

Polished slabs were examined using the Damage Rating Index developed by P. Grattan-Bellew (Dunbar and Grattan-Bellew, 1995). The ratings are shown in Figure 7. All of the values ranged from 50 to 60 except for the high-alkali cement mix, which had 194, indicating extensive damage due to ASR, and for mix 4 with a very low DRI of 5. Values less than about 50 indicate no ASR damage and, in Mixes 1, 2, 3, and 5, most of the ratings are caused by fractures in the coarse aggregate and are not necessarily ASR-related. However, some signs of ASR were found in some of Mixes 1, 2, 3, and 5 using SEM and petrographic analysis.

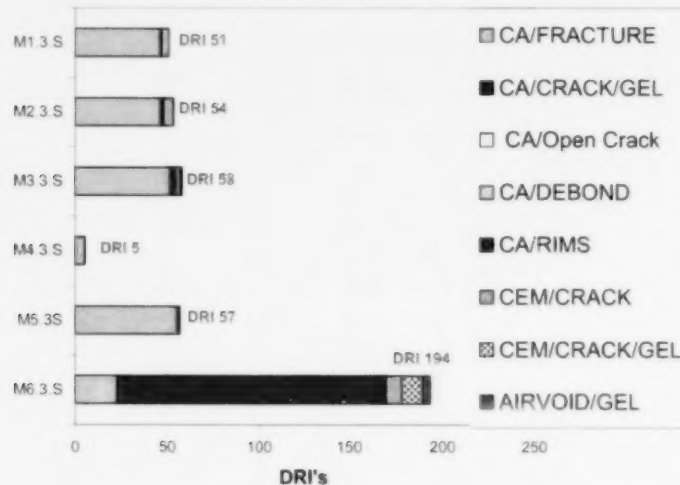


Figure 7. Damage Rating Indices for 12-Year Cores from Outdoor Exposed Slabs

Thin sections of the field concrete taken from the beams and slabs at an age of about 12 years were examined under a petrographic microscope, and polished, epoxy-impregnated sections were examined in the SEM. Concrete from Mixture 6 (high-alkali cement) showed extensive cracking of the coarse aggregate and the cement paste. The amount of cracking was less near the surface of the concrete (e.g. within 25 mm of the top surface of the slabs); it is probable that leaching of alkalis has resulted in less damaging alkali-silica reaction in this zone. Cracks (from about 5 μm to 200 μm in width) were either found running through the aggregate and into the surrounding paste or found inside the aggregate, close to the edge of the aggregate. It was estimated that about 30 to 50% of the coarse aggregate particles showed these internal cracks. The cracks that were found in the cement paste were lined or filled with a clear alkali-silica gel. Air voids close to the cracks were often lined or filled with the same gel (Figures 8 and 9). On fractured surfaces, thin crusts of clear alkali-silica gel were readily found coating irregular large void surfaces or lining air voids. EDX analysis in the SEM indicated that the gel found in air voids and in cracks in the mortar was rich in calcium, whereas the gel found in the opening of cracks in the aggregate had a high-alkali (K^+) content (see Figure 9). The cracks found in the aggregate were not filled with gel, but with an acicular crystalline material with low birefringence (Figures 10 and 11), although some cracks were empty (i.e. did not contain reaction product). In transmitted light, this material had a light-brown colour in thin section and, in reflected light, was either

white or had a light blue colour. The acicular crystalline material had the elemental composition shown in Figure 9 (Spot 4) (i.e. approximately equal amounts of potassium and calcium with minor sodium and a strong indication of silica). This material is similar in appearance and chemistry to that described by Shayan and Lancucki, 1986, who described a crystalline material with x-ray characteristics and chemistry very similar to that of the mineral Okenite ($\text{Ca}_{10}\text{Si}_{18}\text{O}_{46}\cdot 6\text{H}_2\text{O}$). This Okenite-like material has been previously described in concretes with alkali-silica reactive siliceous limestones of Quebec and Ontario by Fournier et al, 1986, as well as with many different aggregates by a number of authors (Shayan and Lancucki, 1986). Not all alkali-silica reactions show this mineral and it is considered uncommon. However, in previous studies of field-damaged concrete from Ontario made with the Spratt aggregate and similar siliceous limestones, this mineral has often been found. It is notable that this Okenite-like material was only found in cracks in the coarse aggregate and was not in the cracks in the adjacent paste where only alkali-silica gel was found, although gel was also typically found in the entrance of cracks in the aggregate up to a depth of $\sim 100\text{ }\mu\text{m}$. Figure 12 shows the transition from brown, birefringent, Okenite-like material in the coarse aggregate to clear gel in that part of the crack in the mortar. The minerals calcite and ettringite were found lining some air voids, but not in excessive amounts.

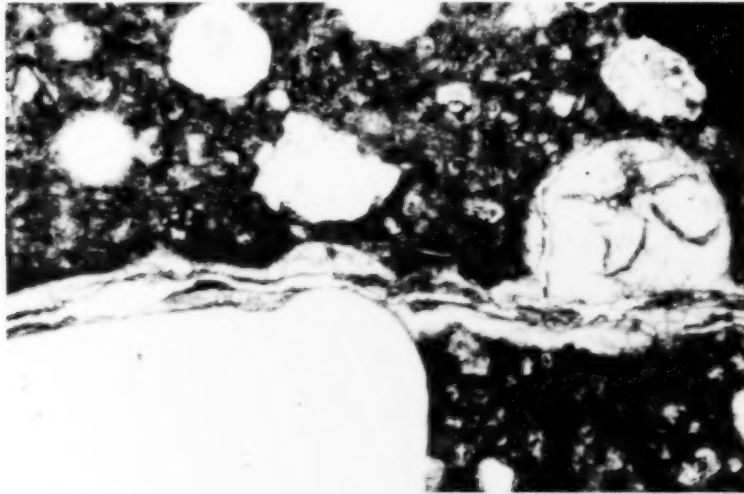


Figure 8. Concrete from Mixture 6 (high-alkali cement), plane light, field of view 0.7 mm. Crack in paste is lined and filled with clear alkali-silica gel as is an oval air void. Light-coloured quartz fine aggregate particle in bottom left.

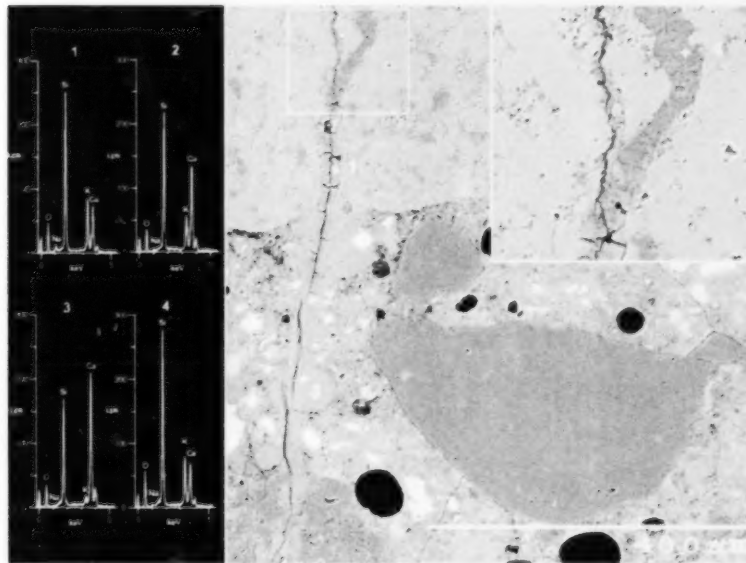


Figure 9. SEM Micrograph of Concrete from Mixture 6 showing alkali-silica gel exuding from a crack in aggregate into a crack and adjacent air voids in surrounding paste.

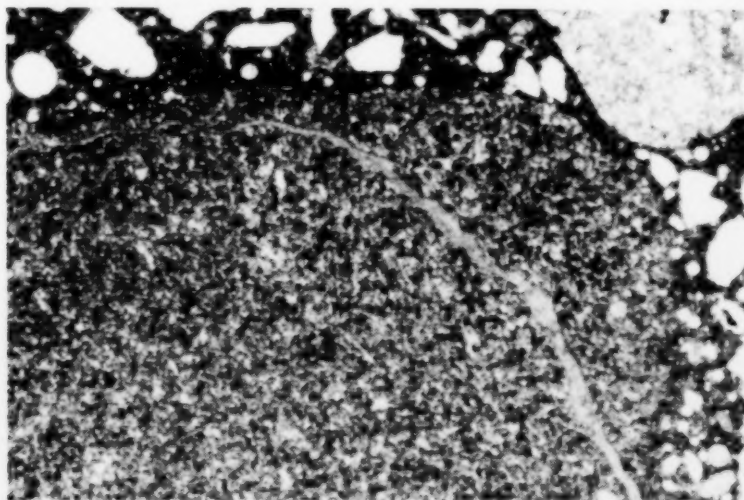


Figure 10. Concrete from Mixture 6 (high-alkali cement), plane light, field of view 4.5 mm. Crack in limestone coarse aggregate is filled with light brown-coloured, crystalline product of ASR.

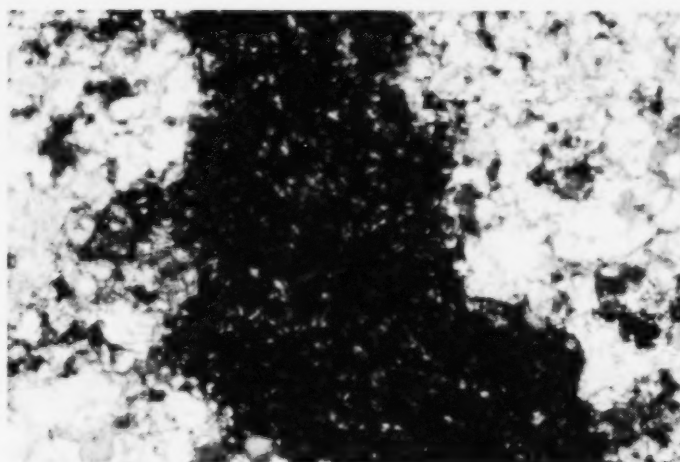


Figure 11. Cherty Limestone, cross-polarized light, field of view 0.35 mm. Crack in coarse aggregate from Mixture 6 (high-alkali cement) is filled with crystalline secondary material; on either side of crack is high birefringence fine crystalline calcite. In cross-polarized light, low birefringence with first order interference colours and clusters of crystals can be seen.



Figure 12. Concrete from Mixture 6 (high-alkali cement) in plane light, field of view 0.7 mm. Coarse aggregate particle of limestone on right is cracked with crack filled with crystalline material. Close to the coarse aggregate boundary with paste the fill material changes to alkali-silica gel.

Mixture 5, which was made with low-alkali cement, also exhibited appreciable signs of alkali-silica reaction and damage, e.g. cracks in aggregate particles with brown birefringent reaction product (Figure 13), cracks extending into the surrounding paste (in some cases, containing ASR gel, but more often not), and air voids adjacent to reactive aggregate particles partially filled with ASR gel. However, the amount of cracking and products of reaction were significantly less than found in Mixture 6.



Figure 13. Cherty Limestone Coarse Aggregate, Mixture 5 (low-alkali cement), plane light, field of view 0.7 mm. Coarse aggregate is cracked with crack filled with light brown-coloured crystalline secondary material. Black areas are pyrite; clear oblong crystal is silica surrounded by sparry calcite.

Mixtures 2 and 3, which contained 18% Type F fly ash and 25% blast-furnace slag, respectively, exhibited signs of ASR. In both concretes, ASR gel was found in cracks and voids in the paste and the Okenite-like material was found in cracks in the aggregates (Figures 14 and 15); however, the number of incidences of damage and reaction product was much less than in Mixture 6 and less than in Mixture 5.

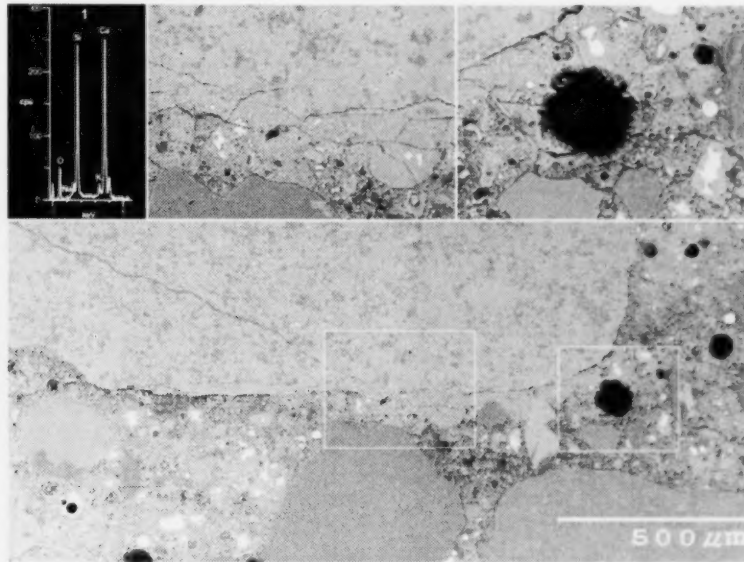


Figure 14. SEM Micrograph of Concrete from Mixture 2 (18% Type F fly ash) showing crack in aggregate with ASR gel flowing into crack and air voids in paste. The gel in the air voids was rich in calcium.

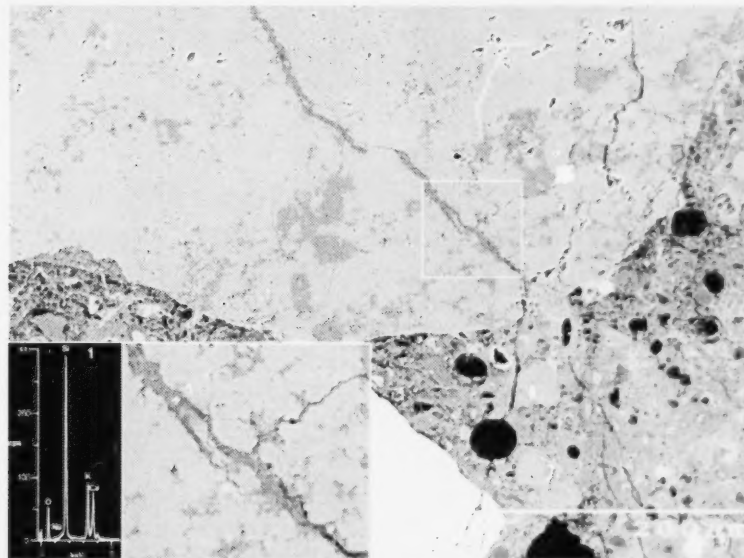


Figure 15. SEM Micrograph of Concrete from Mixture 3 (25% ggbfs) showing a crack in coarse aggregate filled with crystalline mineral and cracks extending in paste.

There were very modest signs of ASR in Mixture 4, which contained 3.8% silica fume and 25% slag. Although not extensive, some fine internal cracks containing the acicular crystalline reaction product were observed in the coarse aggregate particles, with fine cracks extending into the cement paste (Figure 16). The reaction product that was found had a high potassium content similar to that of the brown birefringent Okenite-like material. No ASR gel was found in the paste or in voids.

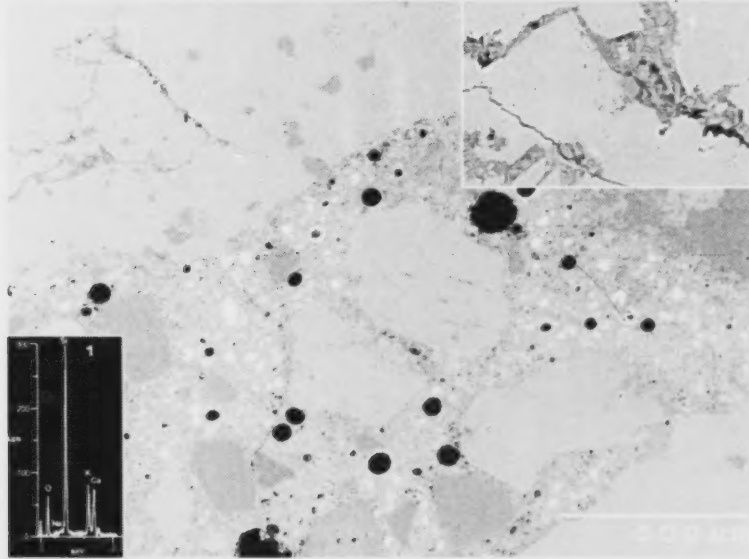


Figure 16. SEM Micrograph of Concrete from Mixture 4 (3.8% sf + 25% GGBFS) showing internal crack in coarse aggregate filled with crystalline reaction product.

No signs of alkali-silica reaction were found in Mixture 1, which contained 50% slag. Some minor cracks were observed in the coarse aggregate, but they appeared to be micro-fractures that were likely caused when the aggregate was crushed.

CORRELATION BETWEEN PETROGRAPHIC/SEM EXAMINATION AND FIELD EXPANSION

The most expansion was obtained with the high-alkali cement mixture (Mixture 6), and it was this concrete that petrographically showed clear and obvious signs of alkali-silica reaction in terms of cracking of concrete, deposits of gel, and internal cracking of coarse aggregate particles.

The concrete beams made with Mixture 5 (low-alkali cement) showed the next largest amount of cracking at an age of 14 years. This concrete was judged petrographically to show the next most obvious signs of alkali-silica reaction after Mixture 6. The observation of small amounts of gel, cracks with "Okenite" in the coarse aggregate are convincing signs that ASR has taken place and explain the expansion after 14 years in the field.

The concrete beams of both Mixtures 2 (18% fly ash) and 3 (25% ggbfs) have shown little cracking. At 8 years, very faint pattern cracking (< 0.005mm) could be seen on parts of the beams generally covering less than 10% of the area. At 14 years, the cracking of Mixtures 2

and 3 was more obvious. Petrographically, the concrete showed signs of alkali-silica reaction but not as clearly as in the low-alkali cement Mixture 5.

Mixture 4 (25% ggbfs, 3.8% silica fume and high-alkali cement) has shown negligible expansion ($< 0.025\%$) in all conditions, and the observed signs of ASR in the concrete are minimal or non-existent. Mixture 1 (50% ggbfs) has shown net contraction in the field and no signs of ASR were observed petrographically.

CORRELATION BETWEEN FIELD AND LABORATORY EXPANSION

Figure 6 shows the relationship between mortar bar expansion and concrete expansion. It should be noted that the 14-day mortar bar test is known not to be valid for determining the benefits of low-alkali Portland cement (Hooton and Rogers, 1989). The Canadian standard for concrete (CSA A23.2-27A, 2004) requires that expansion of concrete prisms be less than 0.04% at 1 year to deem an aggregate to be non-deleteriously reactive. It can be seen that, after 14 years, concrete in outdoor exposure gave less than 0.04% expansion for Mixtures 1 (50% ggbfs) and 4 (25% ggbfs and 3.8% silica fume). These mixtures also gave less than 0.10% expansion in the mortar bar test at 14 days. Currently, the advice given in CSA standards (A3000 and A23.2-28A) is that, when mortar bars give less than 0.10% expansion at 14 days with a reactive aggregate and a supplementary cementing material, the material in the proportion used will prevent deleterious alkali-silica reaction. Data given in Figure 6 confirms this advice.

The persistent expansion and obvious, but as yet minor, damage after 14 years to concrete from Mixtures 2, 3, and 5 raises questions as to whether or not these would be adequate measures to be adopted to prevent ASR. It depends on the reactivity of the aggregate and the environment. Spratt siliceous limestone is regarded as highly reactive, but it is not as reactive as some natural aggregates found in North America. Clearly, the use of 18% fly ash, 25% slag, and low-alkali cement did not completely prevent expansion and resulted in very slight cracking. This might be tolerated in some kinds of concrete construction but not in others where slight expansion or cracking may seriously affect the function of the structure. Examples might be significant highway structures, large dams, and nuclear containment structures. For complete mitigation of ASR, higher replacement levels of SCM's are needed, as evidenced by the excellent performance of the 50% slag and the ternary mixture of 3.8% silica fume plus 25% slag.

CHLORIDE PENETRATION RESISTANCE

From Tables 4 and 5, the chloride bulk diffusion (ASTM C1556) and rapid permeability index (ASTM C1202) results are shown for cores from 12-year-old beams and slabs respectively. The beneficial effects of supplementary cementing materials (SCM's) are clearly shown from the ASTM C1202 results. All of the mixtures with SCM's effectively had coulomb ratings of less than 1000, while the Portland cement Mixtures 5 and 6 were still higher than 1000 after 12 years. For the bulk diffusion tests on the slabs and the interior of the beams, the Portland cement Mixtures 5 and 6 were significantly higher than the SCM Mixtures 1 to 4, with the low-alkali cement giving the highest values. For the bulk diffusion

tests carried out on the surface (outer 50 mm) of the beam cores, there was a much lower surface concentration of chlorides after 42 days ponding for all 6 mixtures. This, in part, resulted in the higher diffusion values obtained for these samples, with the exception of the high-alkali cement Mixture 6. However, it is also likely that the short 4-day moist curing period, combined with skin effects, is responsible for the higher diffusion values of samples tested at the surface. Mixture 6 likely had higher early strength than the other concrete mixtures and was less permeable at the end of the curing period.

The chloride profiles of the exposed slab surfaces (snow was cleared and the slabs were de-iced for the first 5 years) were measured after 12 years. The average depth where chlorides had penetrated to a concentration of 0.05% by mass of concrete was 16.5 mm (Mix 1), 19.5 mm (Mix 2), 17 mm (Mix 3), 16 mm (Mix 4), 31.5 mm (Mix 5), and 29 mm (Mix 6). Portland cement Mixtures 5 and 6 allowed chlorides to penetrate 50 to 100% further than the mixtures with SCM's.

CONCLUSIONS

The outdoor expansion and cracking of slabs and beams, made from six different concretes using alkali-silica reactive aggregate and different cementing materials at 420 kg/m^3 and $w/cm = 0.40$, have been monitored for 14 years. The concrete made with high-alkali cement and no protective measures cracked at an age of 5 years when stored outdoors in the Canadian climate. The expansion levels at the time of cracking ranged from 0.05 to 0.07%. When the high-alkali cement was replaced with various amounts of supplementary cementing materials or low-alkali cement, expansion was considerably less and only very minor cracking occurred. When sufficient SCM's were used, there was no sign of ASR or cracking. Petrographic examination showed that there was a correlation between signs of ASR in the concrete and field expansion and damage.

The following materials have been shown to be more or less effective: 50% and 25% ground granulated blast-furnace slag, 18% Type F fly ash, low-alkali cement ($< 0.6\% \text{ Na}_2\text{Oe}$), but minor cracking and early signs of ASR exist. The most effective measure at preventing damaging ASR that also had adequate freeze/thaw scaling resistance was a ternary blend of 25% slag and 3.8% silica fume interground with a high-alkali Portland cement. It was found that the use of 50% slag, while very effective at preventing ASR, may result in a concrete with lower resistance to freeze/thaw de-icer scaling of pavement slab surfaces. However, the minor scaling of the 50% slag slabs exposed only some of the coarse aggregate after the first winter and has not worsened since then.

It was found that the data confirm the advice given in CSA standards that, when mortar bars give less than 0.10% expansion at 14 days with a reactive aggregate and a supplementary cementing material, the material in the proportion used will prevent deleterious alkali-silica reaction.

In addition, the concretes with SCM's had superior chloride resistance properties to the pure Portland cement mixtures, as measured by both bulk diffusion and ASTM C1202 coulomb results.

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